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14. ABSTRACT

An advanced CW laser induced fluorescence diagnostic technique, capable of correlating high frequency current fluctuations to the resulting fluorescence excitation lineshapes, has been developed. This presentation describes this so-called ``Sample-Hold" method of time-synchronization, and provides the steps taken to validate this technique, including simulations and experimental measurements on a 60 Hz Xe lamp discharge. Initial results for time-synchronized velocity measurements on the quasi-periodic oscillatory mode of a magnetic cusped plasma accelerator are also presented. These results show that the positions of the ionization and peak acceleration regions in the device vary over the course of a discharge current oscillation.

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Development of a Time Synchronized CW-Laser Induced Fluorescence Measurement for Quasi-Periodic Oscillatory Plasma Discharges

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Outline

- Introduction
  - Motivation for research
  - Laser Induced Fluorescence (LIF) velocimetry
- Sample-Hold Method
  - Digital
  - Hardware
- Time-synchronized LIF characterization
  - Modeling of time-synchronization schemes
  - Table-top experiment results
  - DCFT experiment results
- Conclusions & Future Work

MIT Diverging Cusped Field thruster

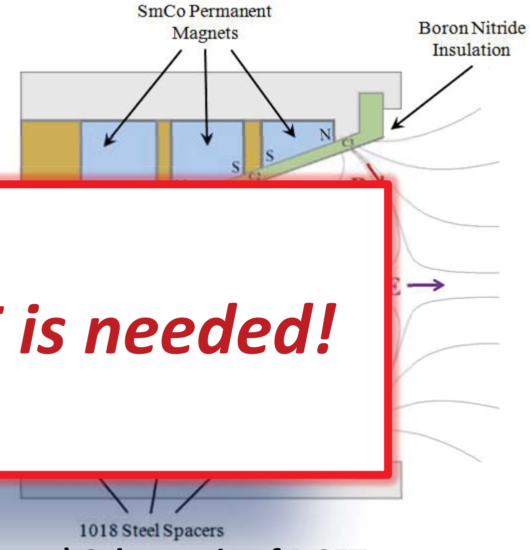
Motivation

- LIF velocimetry diagnostics applied to the Diverging Cusped Field Thruster (DCFT)
  - Low Current Mode

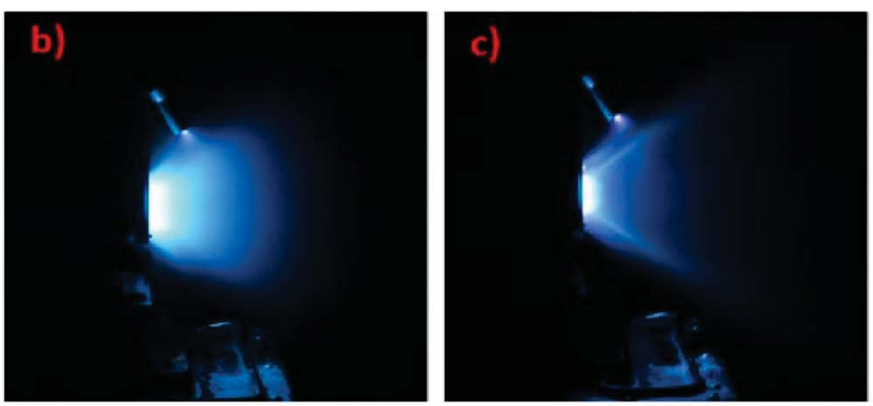
A Time-Synchronized method of CW-LIF is needed!

  - Discharges typically operate on xenon
    - Spectral linewidths and shifts that are too narrow to resolve with pulsed dye lasers

a)

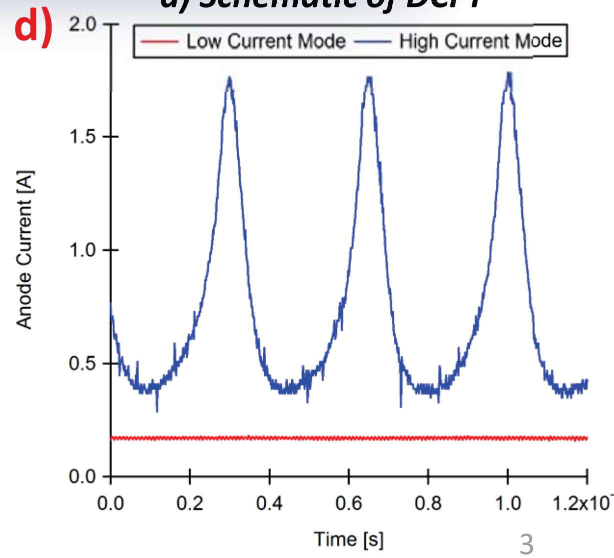


a) Schematic of DCFT



DCFT operating in: b) High current mode, c) Low current mode

d)



d) DCFT Current Traces

Laser-induced Fluorescence Velocimetry

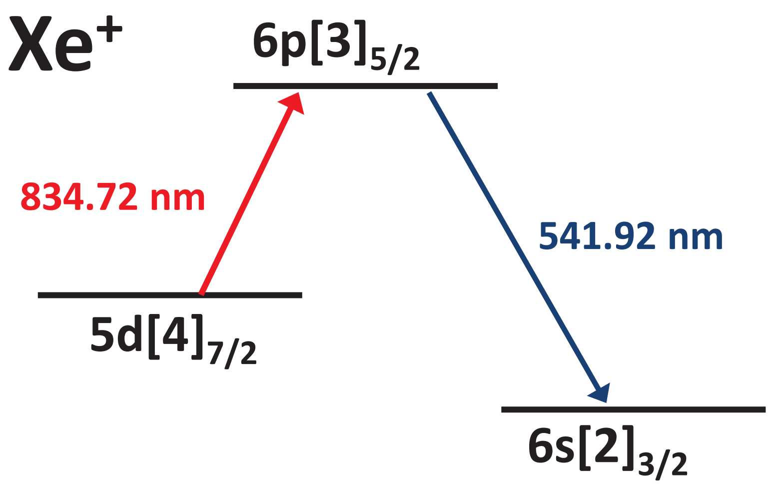
LIF is used to measure the velocity of ions in the thruster plume

- Laser beam tuned across electronic transition in Xe ions

  $5d[4]_{7/2}$–$6p[3]_{5/2}$ at 834.72 nm

- Ions spontaneously emit photons resulting in their relaxation from its excited state to a lower state (fluorescence)

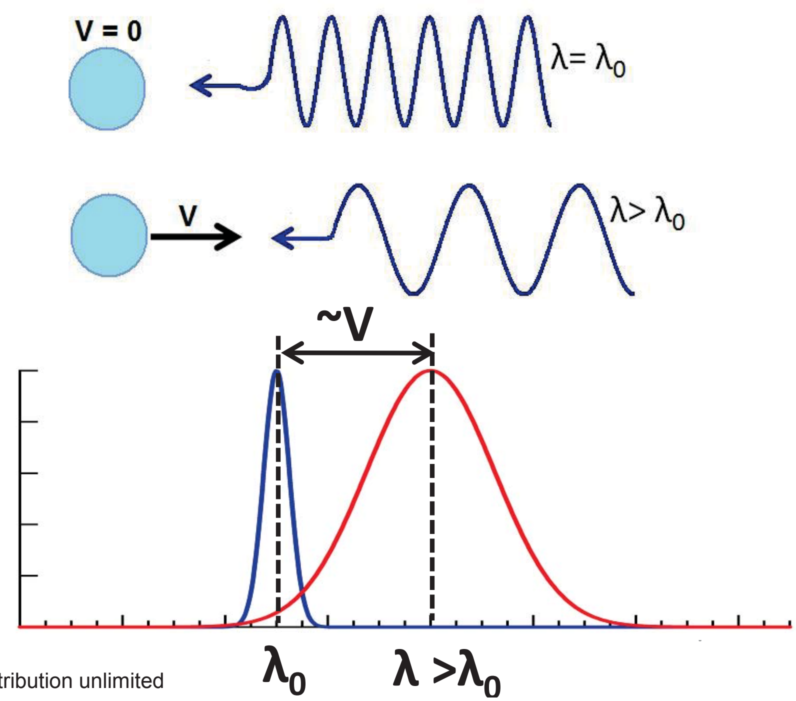
  $6s[2]_{3/2}$ –$6p[3]_{5/2}$ at 541.92 nm



Non-resonant fluorescence scheme

- Fluorescence excitation spectrum = convolution of ion velocity distribution function (VDF), and transition lineshape (inc. hfs, etc.)
- Shape (broadening/shift) dominated by Doppler effect:

$$\delta\nu_{12} = \frac{V}{c}\nu_{12}$$



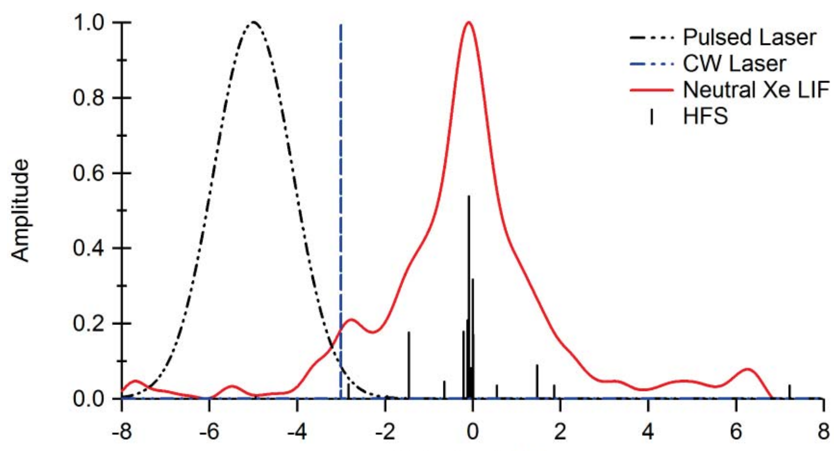
Approaches to Time-Synchronization

Option 1:

- Use pulsed laser to make time resolved LIF measurements

Issues:

- Typical linewidth of pulsed laser is larger than desired
  - Pulsed Nd:Yag Pumped Dye Laser: > 1.5 GHz
  - Typical Doppler width of transition: < 2 GHz



Lineshape of the 834.68 nm Xe transition compared to widths of a pulsed laser and a CW laser. Hyperfine structure (HFS) shown as reference.

Option 2:

- Use CW diode laser to take time resolved LIF measurements
  - CW Diode Laser: < 300 kHz

Approach:

- Take advantage of periodicity of thruster discharge
  - Synchronize acquisition of fluorescence signal with oscillating discharge current
- Two methods considered
  - Boxcar Averager
    - Adds signals in time domain when chopper is open, subtracts when chopper is closed
  - Sample-Hold
    - Uses phase-sensitive detection to remove background

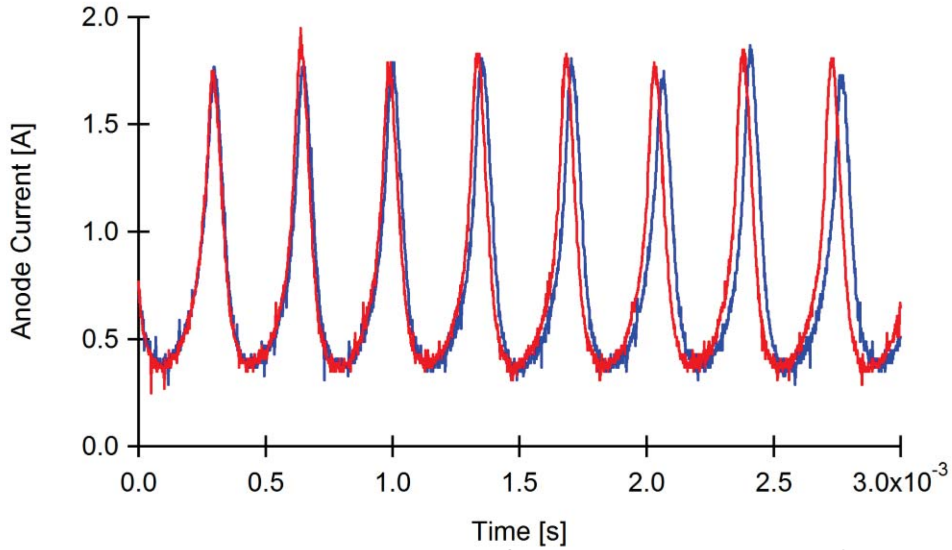
Why Sample-Hold?

Boxcar Averager

- Boxcar averager method is more similar to previous studies, including measurements of velocity or energy distributions in:
  - Hall thruster[1]
  - Magnetic field reconnection in a toroidal shaped plasma device[2]
  - Helicon generated pulsed argon plasma[3]
- In previous studies, plasma discharge was driven at a particular frequency
- DCFT is naturally *quasi*-periodic
  - Straight addition and subtraction of current cycle signals are not effective
  - Signals have to be stretched or interpolated such that they cover the same amount of time, introducing error

Sample-Hold

- Phase sensitive detection allows for jitter in frequency of discharge current
- Sample-hold method can get good result with fewer scans
- For small signals that can't be pulled out by boxcar averager method or digital lock-in, hardware version of sample-hold is available
  - High dynamic reserve of SR-850 Lock-In



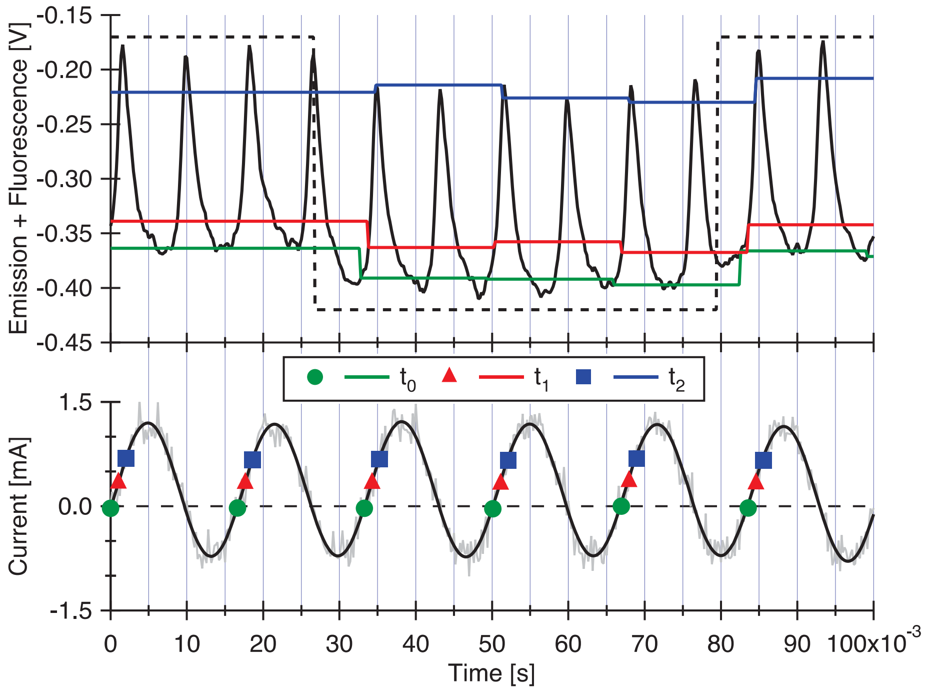
DCFT current traces, taken approx. 30 seconds apart. Note: slight change in frequency

References:

1. S. Mazouffre, D. Gawron, and N. Sadeghi. Phys. of Plasmas **16**, 1 (2009).
2. A. Stark, W. Fox, J. Egedal, O. Grulke, and T. Klinger. Phys. Rev. Lett. **95**, 1 (2005).
3. I. A. Biloiu, X. Sun, and E. E. Scime. Rev. Sci. Instrum. **77**, 10F301-1 (2006).

Digital Sample-Hold Method

- Simultaneous measurements of discharge current, emission + fluorescence
- Zero point crossings of discharge current with positive slope are located
  - Crossing points considered as time = t_0
  - Times t_1 , t_2 , etc. determined based on a delay time with reference to the t_0 points
- Emission plus fluorescence trace is sampled at the first data point corresponding to time = t_0
- This value is held until the current cycle reaches its next positive zero crossing
- Emission plus fluorescence trace is re-sampled and held until the next crossing
- This process is repeated for times t_1, t_2, …, splitting emission plus fluorescence trace into N separate signals corresponding to N times within the current cycle

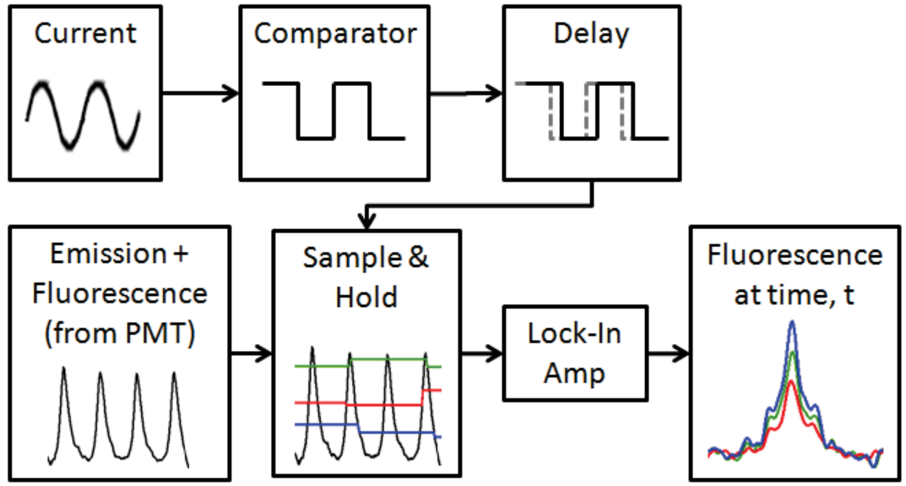


Discharge current, with points for time t_0 through t_2 (bottom). Raw PMT signal ---, chopper on/off - - -, and sample-held signals for t_0 through t_2 (top).

- The individual sample-held signals are passed through digital lock-in amplifier to pull out time-synchronized fluorescence excitation lineshapes

Hardware Sample-Hold Method

- AC current from the Xe lamp discharge is fed into an LM339 comparator chip
  - Comparator output is +5 V when signal from current is above 0.005 V, and 0 V when current signal is below 0.005 V
  - Comparator is configured with a hysteresis circuit to prevent over-triggering
  - Output of comparator is a series of transistor-transistor logic (TTL) pulses with ~50% duty cycle
- TTL Pulses from comparator trigger sample-hold on a Stanford Research Systems SR-250 Boxcar Averager
  - Other SR-250 inputs/settings:
    - Raw emission plus fluorescence from PMT
    - Gate width = 15μs
    - Delay time = 0 to 160 ms
  - Positive slopes in TTL trigger the boxcar averager to sample the PMT signal for a period of time defined by the gate width
  - The last sampled value of the PMT signal is held until the next TTL trigger
  - Boxcar averager re-samples the PMT signal and holds the value again

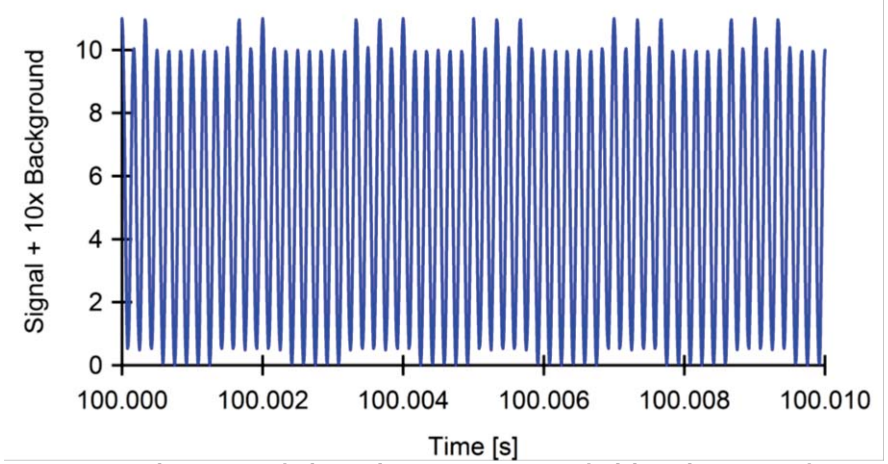


Block diagram of hardware sample-hold method

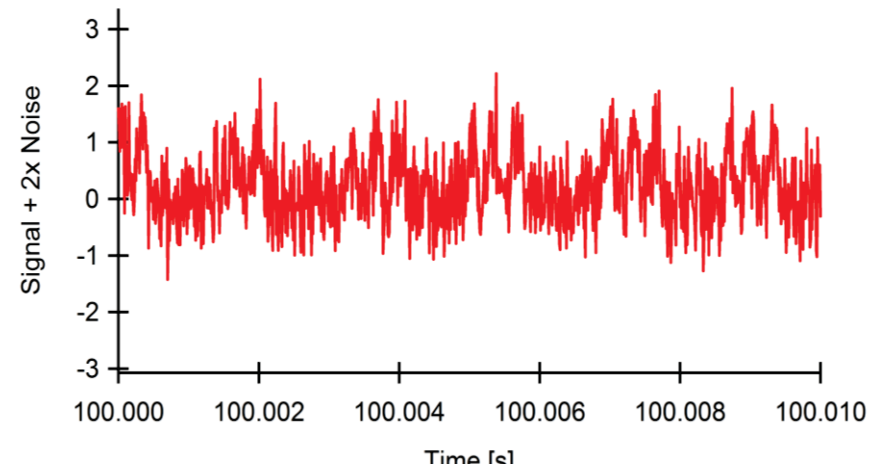
- Sample-held output is fed directly into an SRS SR-850 Lock-in Amplifier
  - Phase sensitive detection at chopper reference frequency
  - Output is a fluorescence excitation lineshape synchronized to time t_0 in the current discharge cycle
- To sample additional times along the current cycle, built in time delay in the SR-250 is used to adjust the sample trigger

Modeling of Time-Sync Method

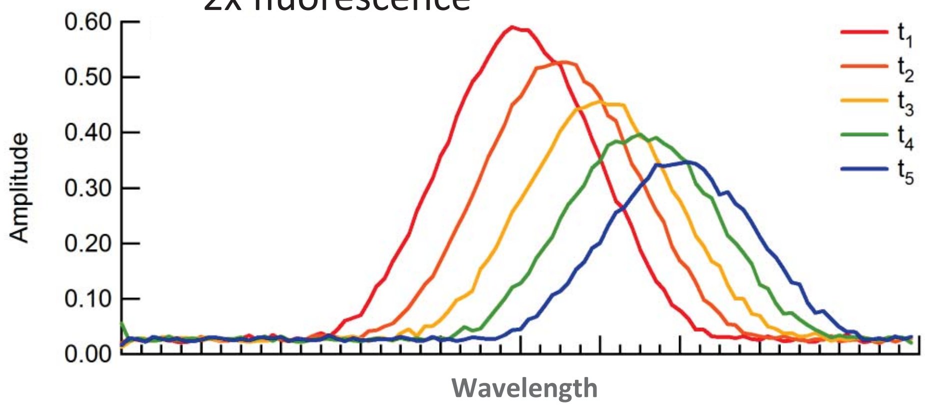
- 3 kHz model – Similar to velocity and amplitude changes expected in DCFT
  - 5 levels of Gaussian profiles with different height and centerline frequency imbedded in chopper on/off signal
  - Background added to fluorescence signal to test noise rejection
  - Successfully rejects noise, including:
    - Sinusoidal background with frequency = 2x current frequency, amplitude = 10x to 1,000x fluorescence
    - Gaussian background noise, amplitude = 2x fluorescence



3kHz model with 10x sinusoidal background

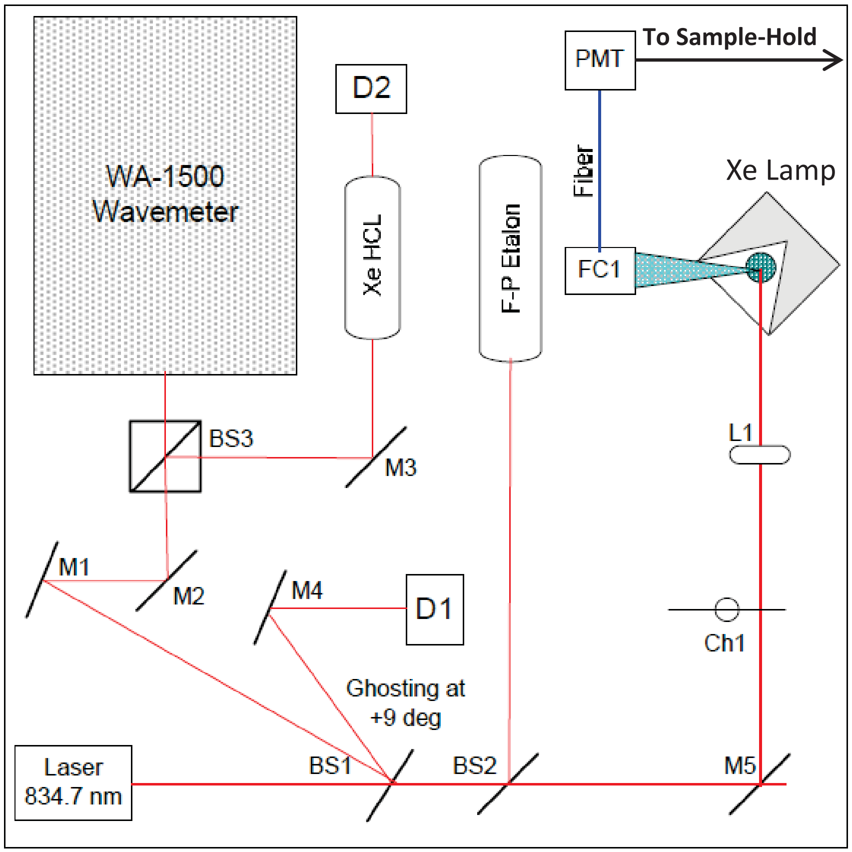


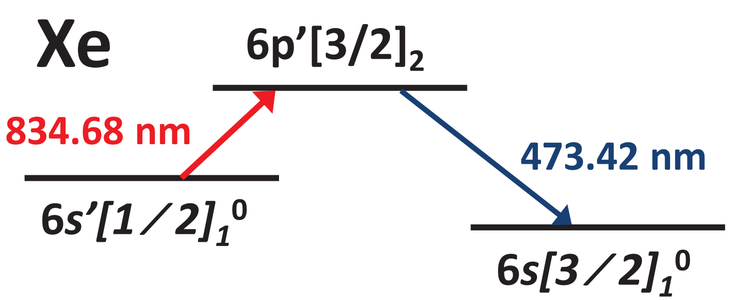
3kHz model with 2x noise



Results of sample-hold method on 3kHz model with 2x noise

Table-Top Experiment

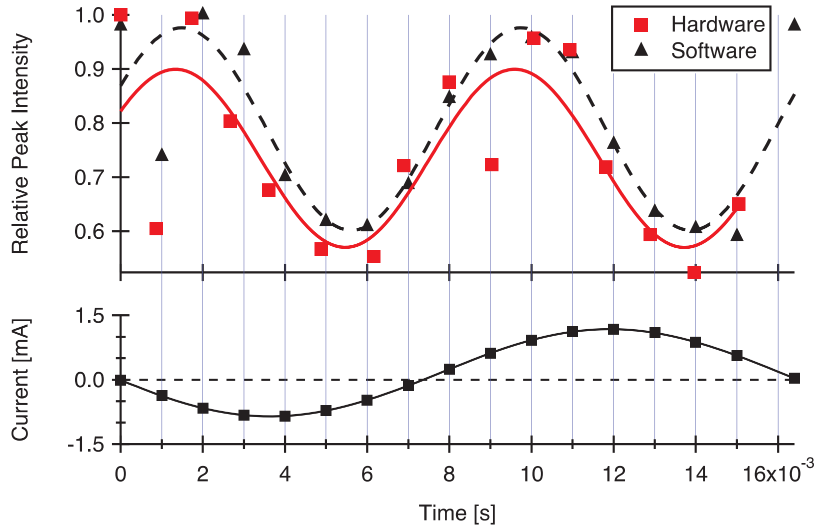




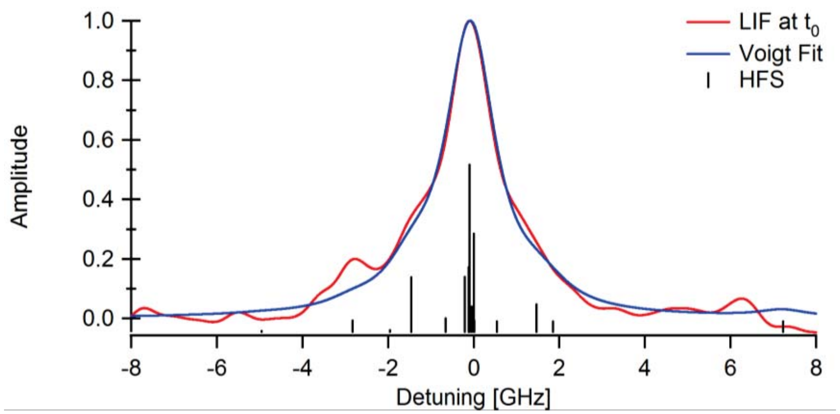
- Measurements on 60 Hz Xe spectral lamp
  - Measuring change in lower state population rather than shift in wavelength
  - Population inferred by time-sync LIF intensity
- Neutral (Xe I) transition at 834.68 nm probed
  - $6s'[1/2]_1^0 - 6p'[3/2]_2$
- Non-resonant fluorescence collected at 473.42 nm
  - $6s[3/2]_1^0 - 6p'[3/2]_2$
- Collected light is coupled to an optical fiber and onto a PMT and sent to Sample-Hold
  - 10 nm BP filter centered at 470 nm
- Two implementations of sample-hold
  - Digital/Software
  - Analog/Hardware

Xe Lamp Results

- Peak intensities of fluorescence excitation lineshapes oscillate at 120 Hz
  - Indicative of the lower state population of the $6s'[1/2]^0_1 - 6p'[3/2]_2$ Xe transition
  - Digital and analog versions of sample-hold give similar results
- Background emission also oscillates at 120 Hz
  - Indicative of the upper state population of the $6s'[1/2]^0_1 - 6p'[3/2]_2$ Xe transition
- Phase delay seen between current, emission and fluorescence intensity peaks
  - Emission delays may be caused by development and diminishment of sheaths at each electrode
  - LIF delay may reflect a difference in mechanism for populating lower and upper states, although they appear closely coupled
- Width of transition changes slightly with time
  - Changes in width are not well correlated with current fluctuations
  - Transition appears pressure broadened
    - P ≈ 7 torr (comparing to results from Cedolin thesis)
  - More information about the lamp is required for temperature estimates



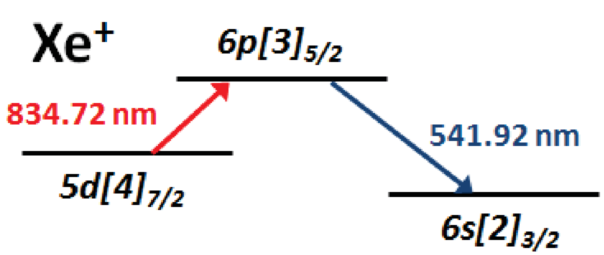
Time evolution of the peak intensities of the fluorescence excitation lineshape over a single current cycle

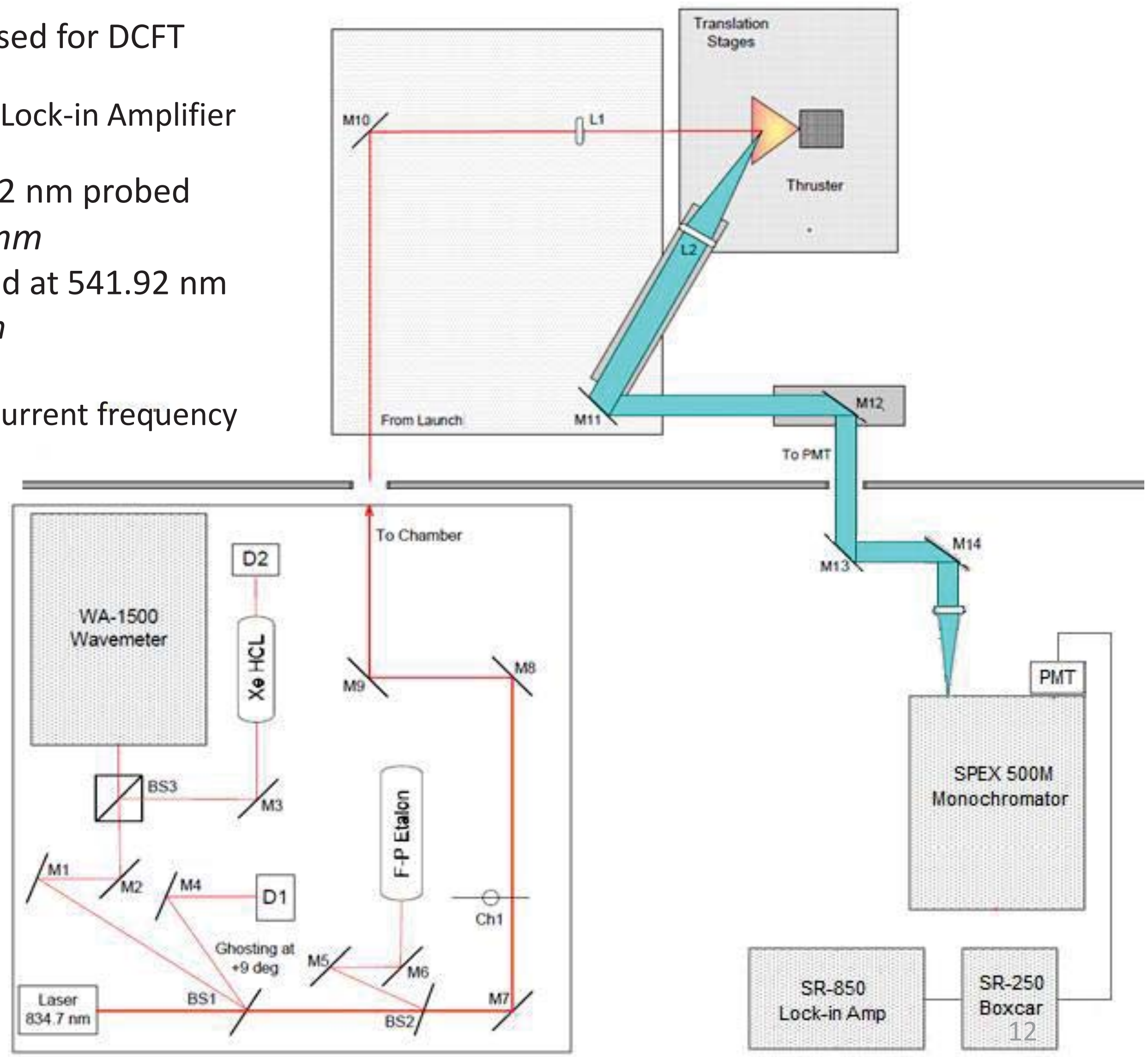


Best Voigt fit of transition at time = t_0 assuming Doppler temperature of 300 K and a = 2.7

Time-Sync DCFT Experiment

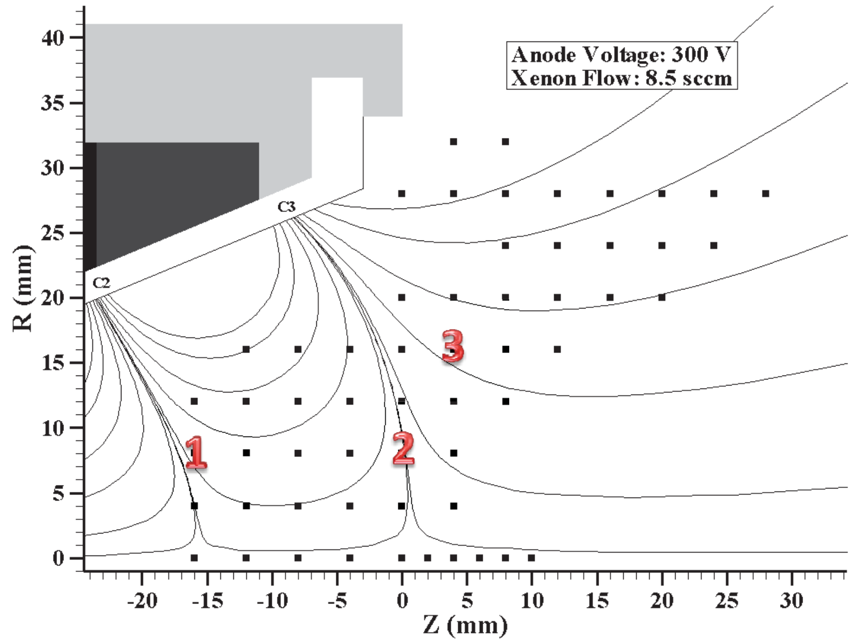
- Hardware version of sample-hold used for DCFT experiments
  - High dynamic reserve of SR-850 Lock-in Amplifier gives better noise rejection
- Xenon ion (Xe II) transition at 834.72 nm probed
  - *$5d[4]_{7/2}$–$6p[3]_{5/2}$ at 834.72 nm*
- Non-resonant fluorescence collected at 541.92 nm
  - *$6s[2]_{3/2}$ –$6p[3]_{5/2}$ at 541.92 nm*
- Chopper frequency at 400 Hz
  - Must be slower than discharge current frequency for sample-hold





Time-Sync DCFT Experiment

- Time-sync LIF measurements made at 3 points in plume
  - Point #1: R = 8 mm, Z = -16 mm
    - Inside channel, near separatrix at cusp #2 (C2)
    - Likely a region of ionization
  - Point #2: R = 8 mm, Z = 0 mm
    - At exit plane, near separatrix at cusp #3 (C3)
    - Close to region of maximum potential drop/ion acceleration
  - Point #3: R = 16 mm, Z = +4 mm
    - In "jet" region of plume

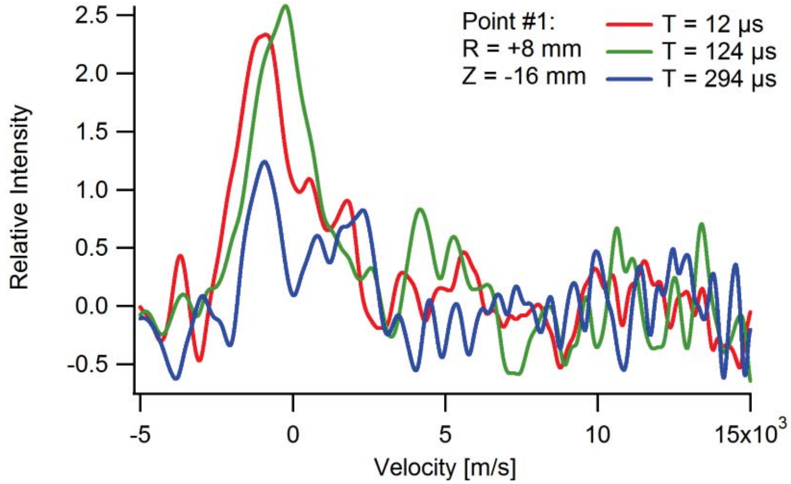


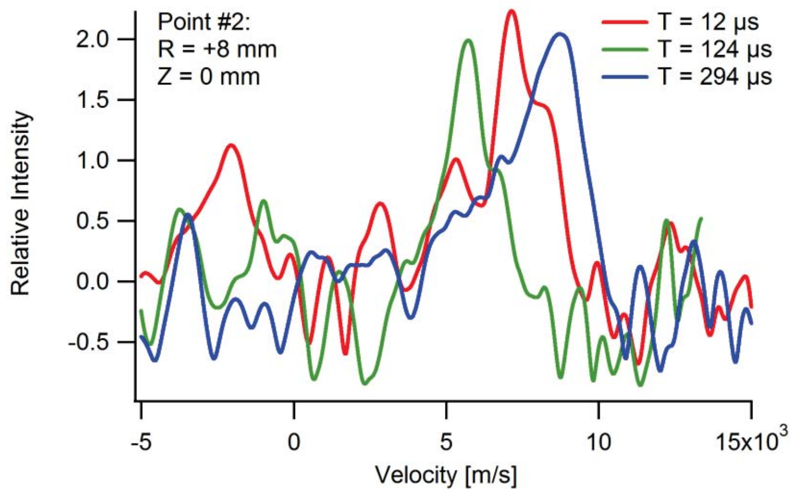
Measurement locations for time-sync LIF on DCFT

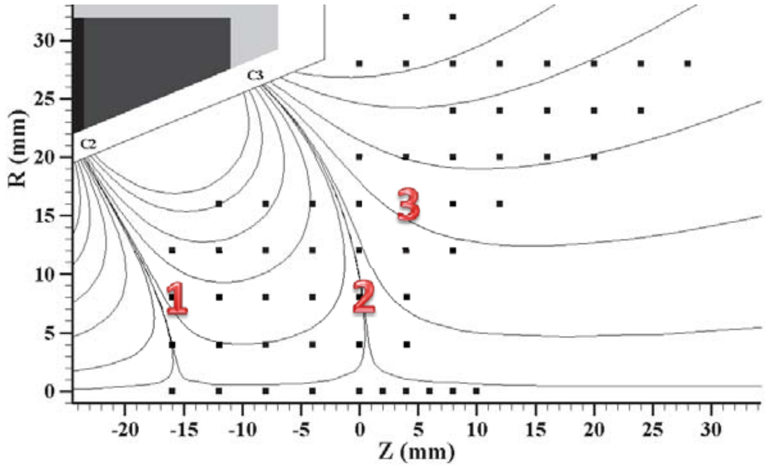
DCFT Operating Conditions	
Anode Flow Rate:	830 µg/s Xe (8.5 sccm)
Anode Potential:	300 V
Anode Current:	0.49 A
Background Pressure:	5×10^{-6} torr

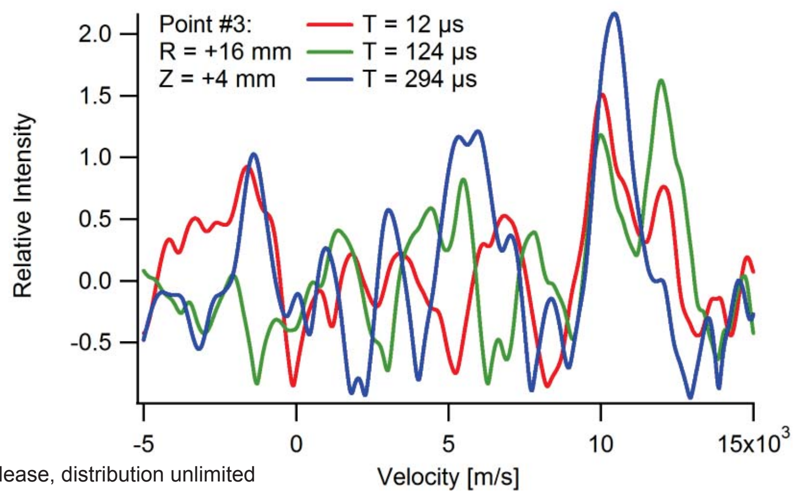
Time-Sync DCFT Results

- Current oscillations driven by accumulation and expulsion of ions within the thruster channel
- Axial velocities change over the course of a single current cycle
- Do positions of ionization and acceleration regions shift over time?



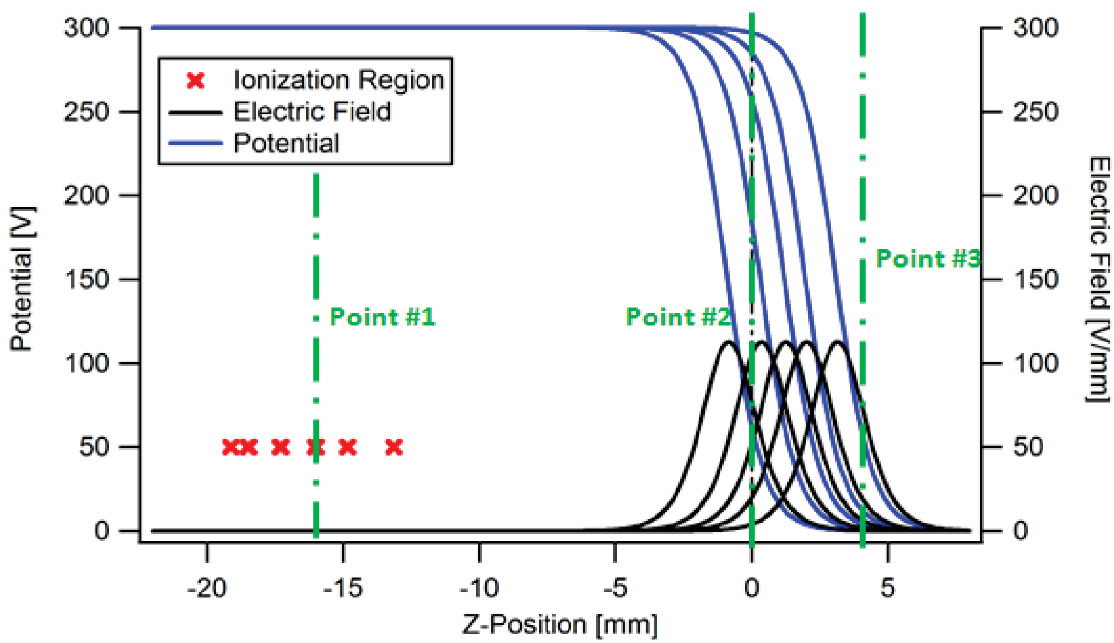






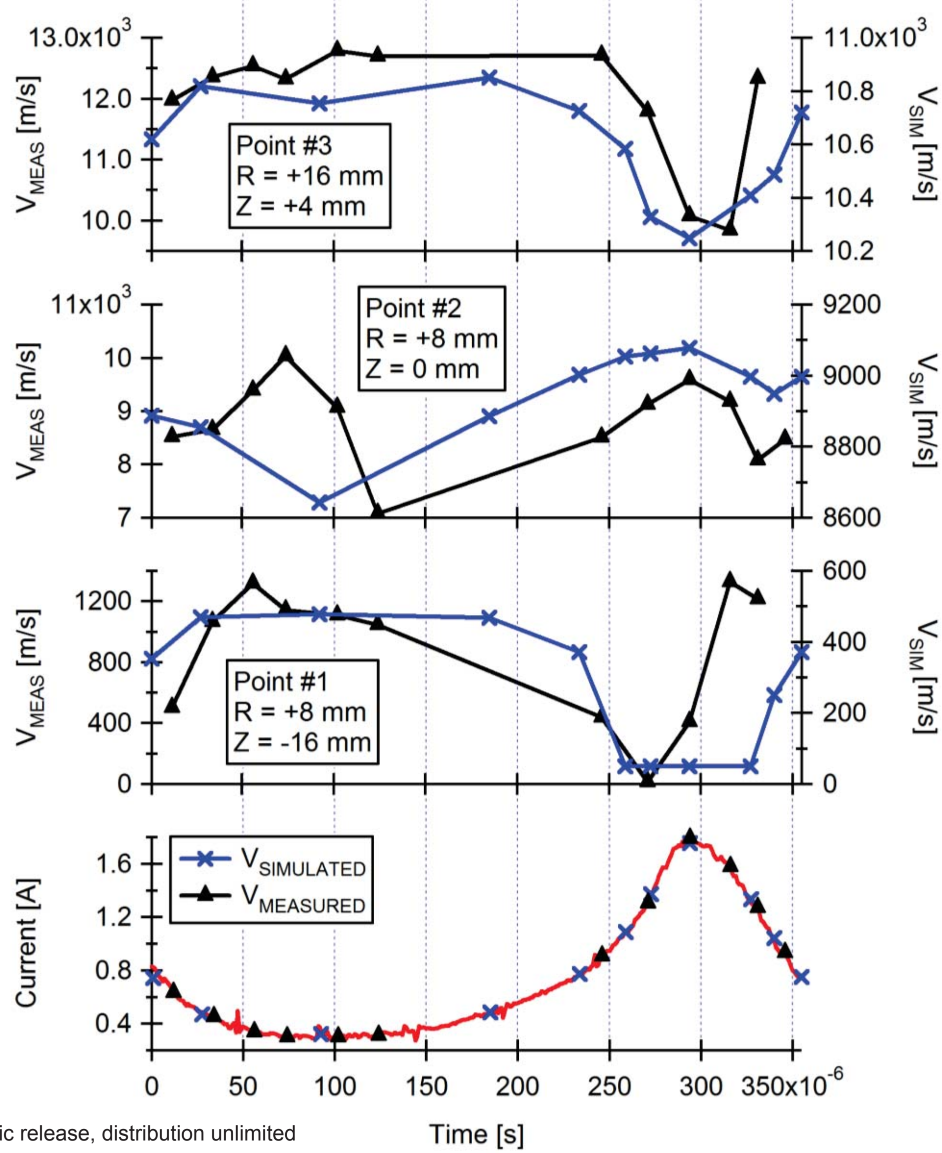
Simulation of DCFT Results

- 1-D Matlab code written to simulate acceleration of ions
- Assumptions:
  - Position of ionization and acceleration regions oscillate proportional to current fluctuations
  - Ionization region oscillates around Z = -16 mm
  - Peak electric field oscillates around Z = +2 mm
  - Electric field only considered in ion acceleration



Analysis of DCFT Results

- Point #1: R = 8 mm, Z = -16 mm
  - Ionization region moves back and forth across separatrix at second cusp, correlated in time to current pulses
  - Times when ionization region is deeper in the channel have higher velocity
  - When ionization region starts to pass Z = -16 mm, velocity is slower
- Point #2: R = 8 mm, Z = 0 mm
  - Position of largest potential drop/peak electric field moves back and forth across outermost separatrix, correlated in time to current pulses
- Point #3: R = 16 mm, Z = +4 mm
  - Past peak acceleration region
  - Ions continue on ballistic trajectories determined in regions similar to Point #1 and #2



Summary

- Sample & hold/phase sensitive detection method has been implemented in software and hardware to synchronize fluorescence signal to discharge current
- Table-top measurements on Xe spectral lamp validated method for both software and hardware versions of sample-hold
- Time-sync measurements made at several positions in the plume of the DCFT
- Current oscillations appear similar to a breathing mode seen in Hall thrusters

Future Work

- Increase S/N for time-sync on the DCFT by using higher power laser
- With increased S/N, make more extensive (spatially) measurements throughout the plume of the DCFT
- Time-synchronized LIF measurement could be applied to other quasi-periodic discharges in fields such as combustion, materials processing, etc.

Thank You!

- Stanford Plasma Physics Laboratory
  - Prof. Mark Cappelli

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- Air Force Research Laboratory, Edwards AFB
  - Dr. Bill Hargus Jr.

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- Air Force Office of Scientific Research, under grant monitor Dr. M. Birkan

Back-up Slides

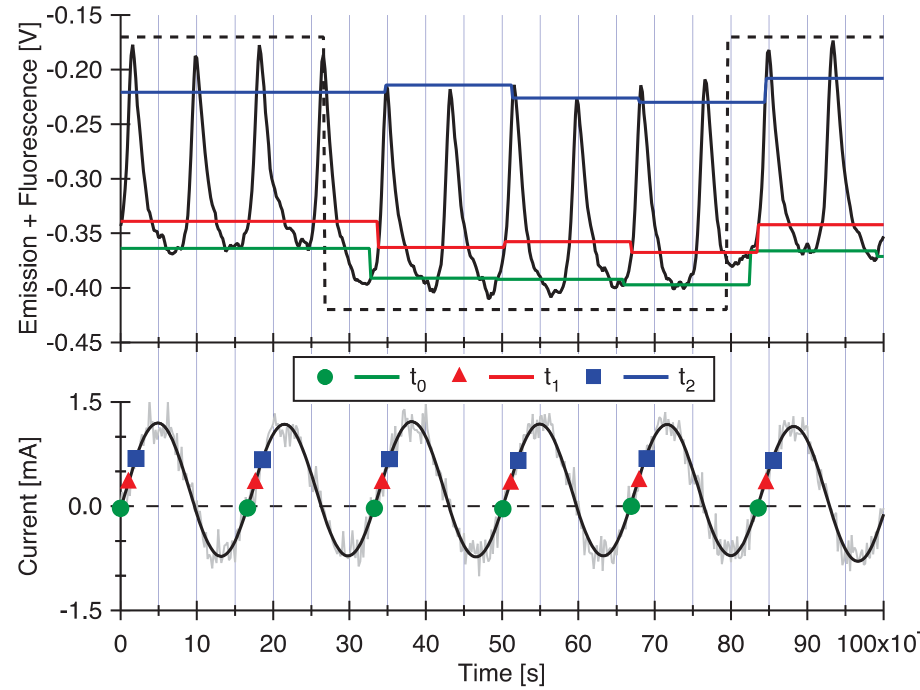
Gated Integration vs. Phase Sensitive Detection

Note: For CW-LIF, mechanical chopper is used to modulate frequency with a 50% duty cycle

- Phase Sensitive Detection (PSD)
  - Locks to chopper reference frequency
  - Maintains noise rejection even if there is jitter in background frequency
- Gated Integration
  - Requires active background subtraction
  - With 50% laser duty cycle, averaging over a large number of on/off cycles is needed to achieve similar results as phase sensitive detection
  - More effective for small duty cycle laser modulation – e.g. for pulsed lasers – where background

Digital Sample-Hold Method

- Simultaneous measurements of discharge current, emission + fluorescence
- Zero point crossings of discharge current with positive slope are located
  - Crossing points considered as time = t_0
  - Times t_1 , t_2 , etc. determined based on a delay time with reference to the t_0 points
- Emission plus fluorescence trace is sampled at the first data point corresponding to time = t_0
- This value is held until the current cycle reaches its next positive zero crossing
- Emission plus fluorescence trace is re-sampled and held until the next crossing
- This process is repeated for times t_1, t_2, …, splitting emission plus fluorescence trace into N separate signals corresponding to N times within the current cycle

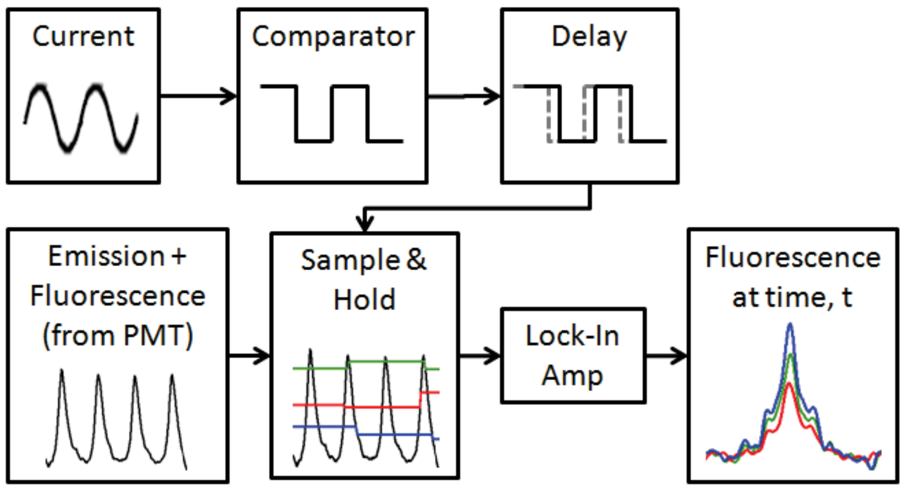


Discharge current, with points for time t_0 through t_2 (bottom). Raw PMT signal ---, chopper on/off - - -, and sample-held signals for t_0 through t_2 (top).

- The individual sample-held signals are passed through digital lock-in amplifier to pull out time-synchronized fluorescence excitation lineshapes

Hardware Sample-Hold Method

- AC current from the Xe lamp discharge is fed into an LM339 comparator chip
  - Comparator output is +5 V when signal from current is above 0.005 V, and 0 V when current signal is below 0.005 V
  - Comparator is configured with a hysteresis circuit to prevent over-triggering
  - Output of comparator is a series of transistor-transistor logic (TTL) pulses with ~50% duty cycle
- TTL Pulses from comparator trigger sample-hold on a Stanford Research Systems SR-250 Boxcar Averager
  - Other SR-250 inputs/settings:
    - Raw emission plus fluorescence from PMT
    - Gate width = 15µs
    - Delay time = 0 to 160 ms
  - Positive slopes in TTL trigger the boxcar averager to sample the PMT signal for a period of time defined by the gate width
  - The last sampled value of the PMT signal is held until the next TTL trigger
  - Boxcar averager re-samples the PMT signal and holds the value again



Block diagram of hardware sample-hold method

- Sample-held output is fed directly into an SRS SR-850 Lock-in Amplifier
  - Phase sensitive detection at chopper reference frequency
  - Output is a fluorescence excitation lineshape synchronized to time t_0 in the current discharge cycle
- To sample additional times along the current cycle, built in time delay in the SR-250 is used to adjust the sample trigger

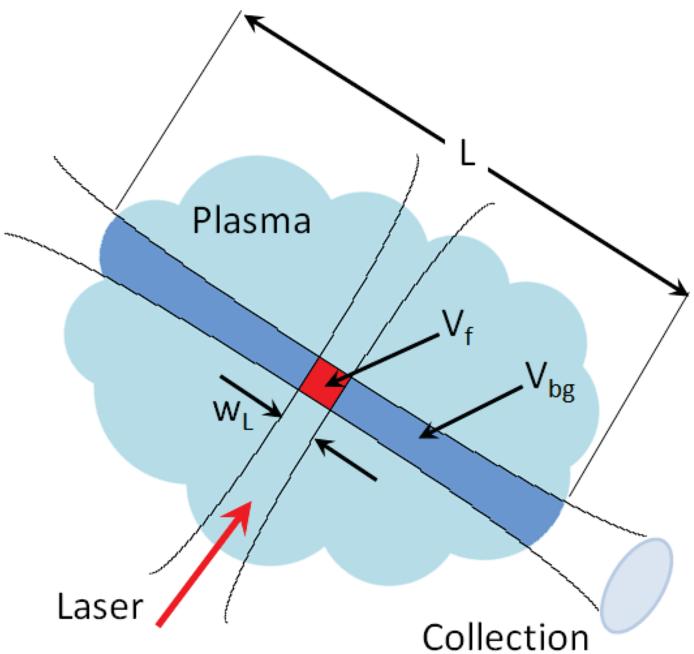
Signal to Background Calculation

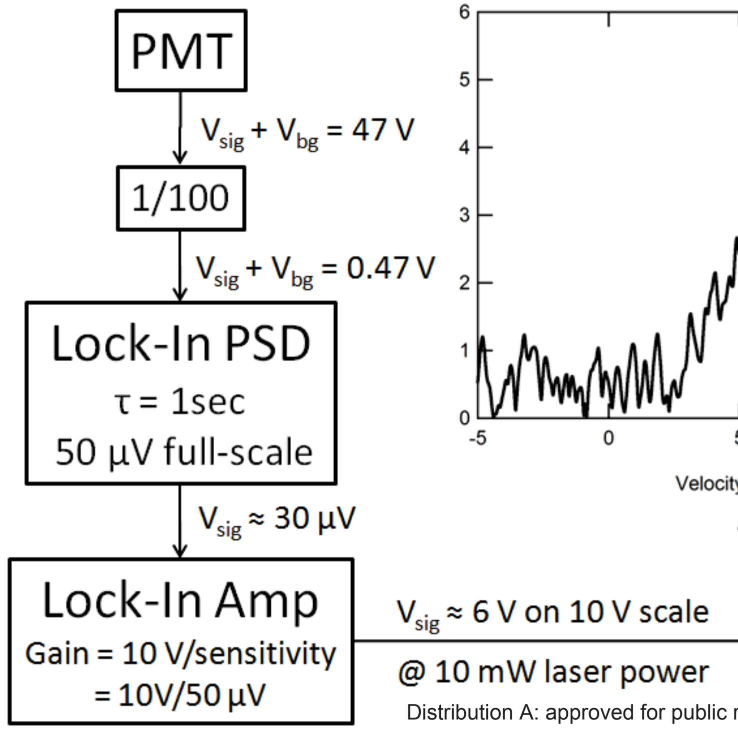
- Collection volume for background emission much larger than for fluorescence

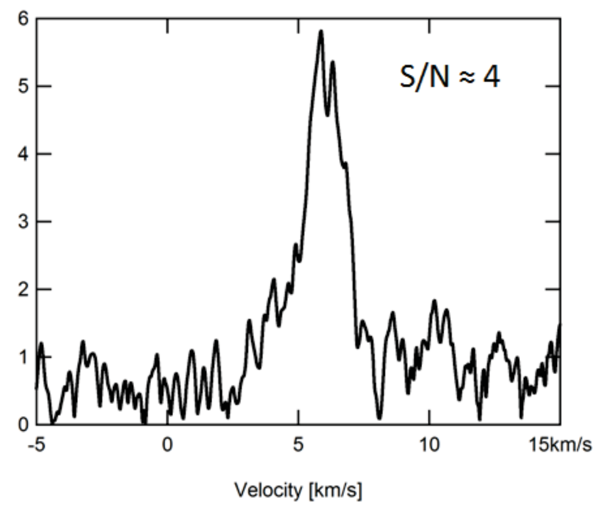
$$\frac{S_f}{S_{bg}} = \frac{n_{2,f} V_f}{n_{2,bg} V_{bg}} = \frac{n_{2,f} w_L}{n_{2,bg} L}$$

$$\frac{S_f}{S_{bg}} = \frac{30 \times 10^{-6}}{0.47} = 6.4 \times 10^{-5} \qquad \frac{w_L}{L} \approx \frac{1}{10} \longrightarrow \boxed{\frac{n_{2,f}}{n_{2,bg}} = 6.4 \times 10^{-4}}$$

- Dynamic reserve of 84 dB necessary to recover fluorescence signal from background

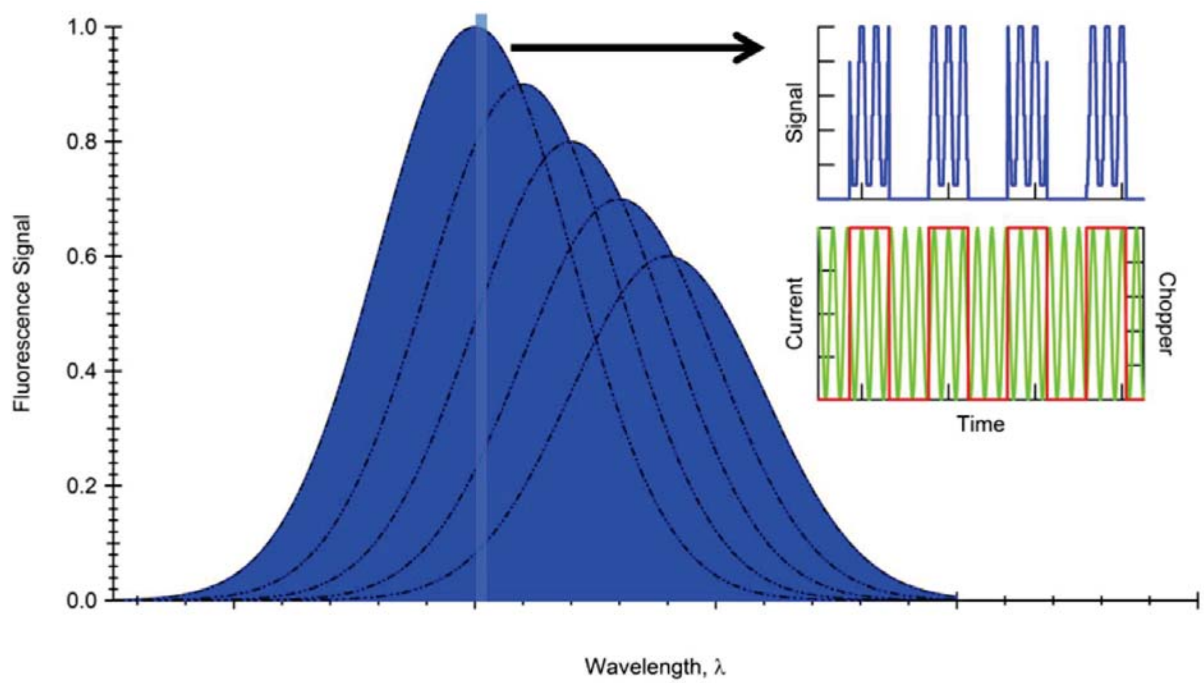






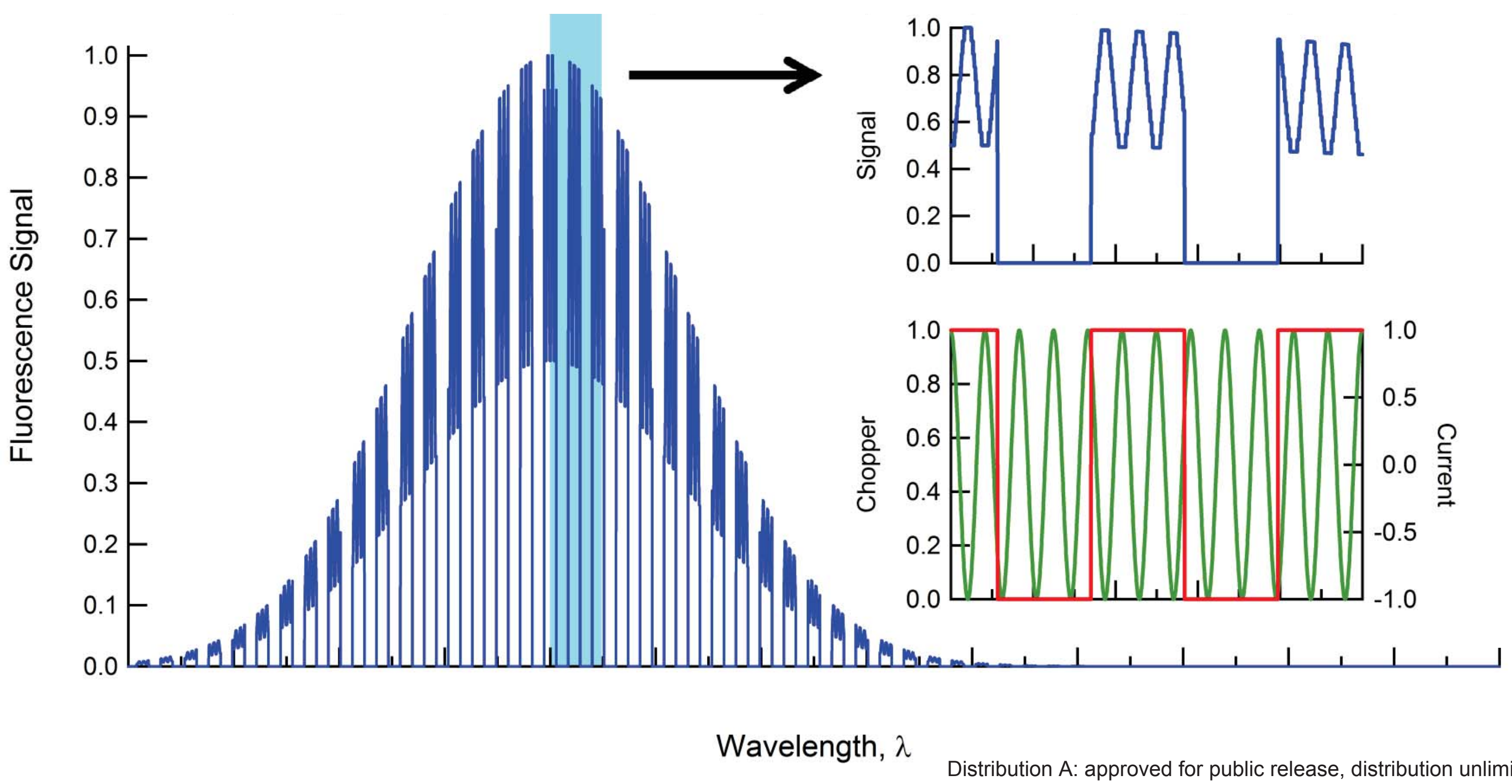
Modeling of Time-Sync Methods

- 3 kHz model – Similar to velocity and amplitude changes expected in DCFT
  - 5 levels of Gaussian profiles with different height and centerline frequency imbedded in chopper on/off signal
  - Background added to fluorescence signal to test noise rejection
    - Sinusoidal background with frequency = 2x current, amplitude = 10x to 1,000x fluorescence
    - Gaussian background noise, amplitude =2x fluorescence



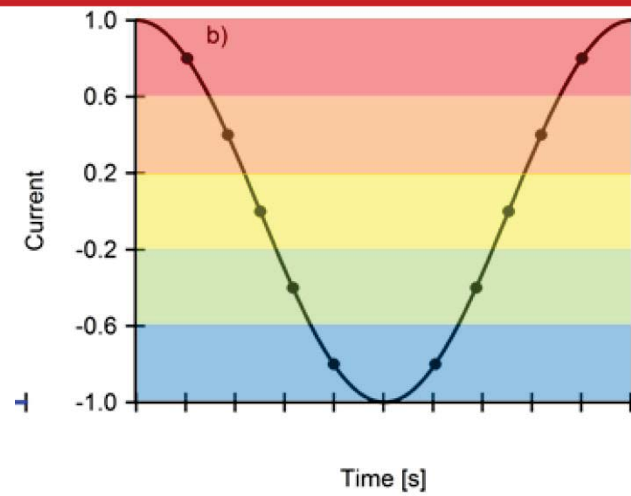
Modeling of Time-Sync Methods

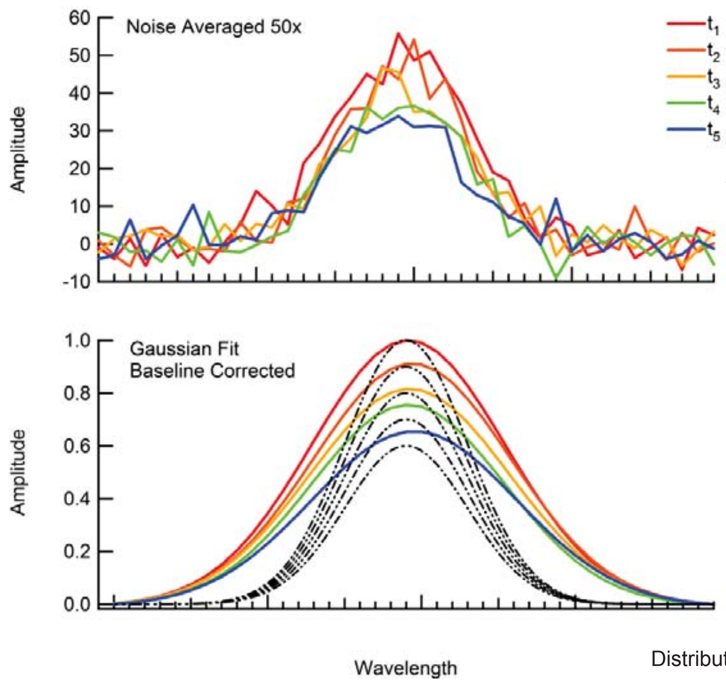
- 60 Hz model – Similar to amplitude changes expected in Xe Lamp
  - 5 levels of Gaussian profiles with different height imbedded in chopper on/off signal
  - Sinusoidal background with frequency = 2x current frequency and/or random background noise added to signal to test
  - Amplitude of background varied from 10x to 1,000x fluorescence signal



Modeling of Time-Sync Methods (cont.)

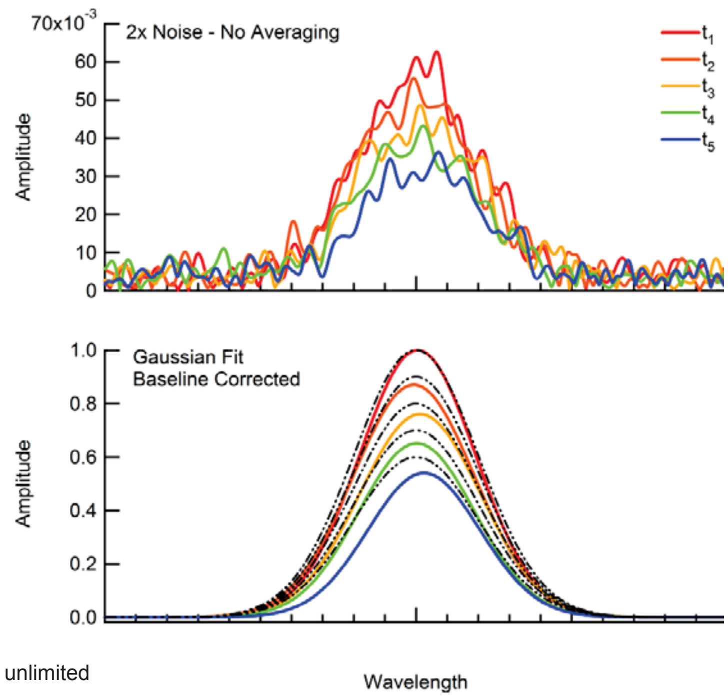
- With 2x Gaussian background noise
  - Boxcar averager method has to be averaged over 50 laser scans to achieve similar results to single sample-hold scan
    - Approx. 15,000 current cycles averaged for each wavelength
  - Boxcar averager also results in significant broadening of lineshape
    - Mainly due to breaking up scan into 40 wavelength sections, vs. sample-hold which is continuous in wavelength space
- With up to 1000x sinusoidal background
  - Both achieve similar results that match well with simulated fluorescence levels





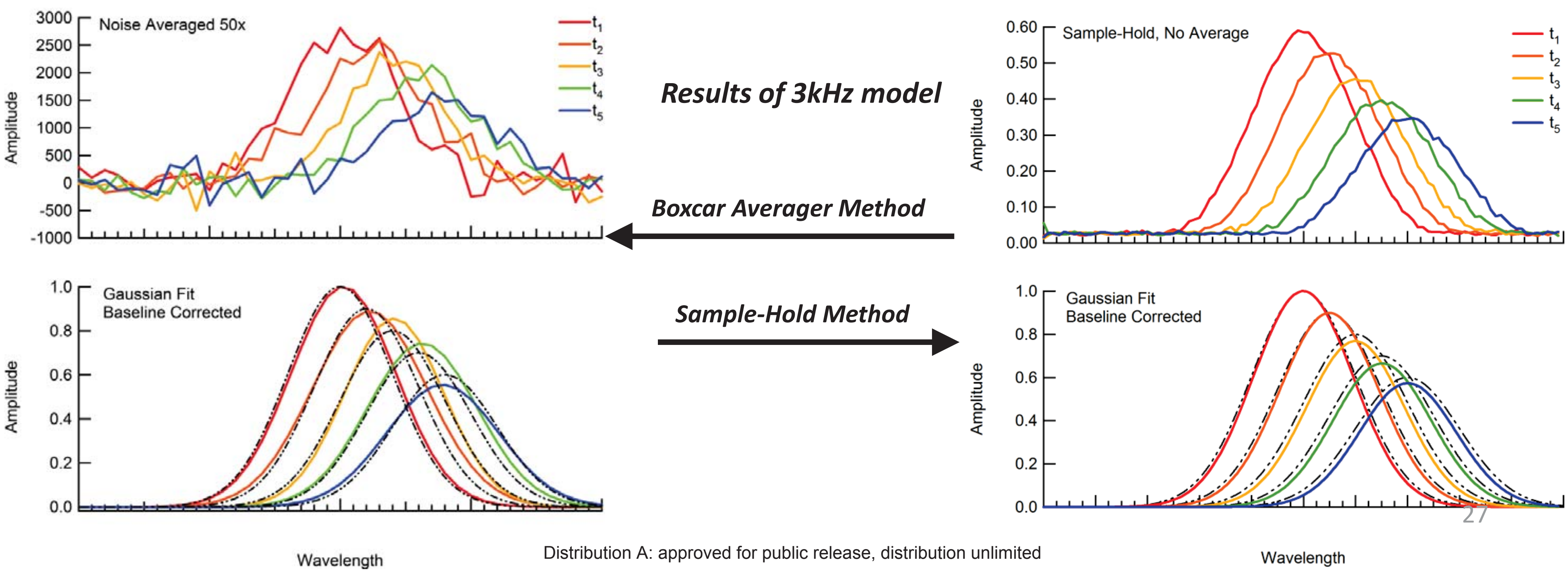
Boxcar Averager Method

Sample-Hold Method



Modeling of Time-Sync Methods

- 3 kHz model – Similar to velocity and amplitude changes expected in DCFT
  - 5 levels of Gaussian profiles with different height and centerline frequency imbedded in chopper on/off signal
- Background added to fluorescence signal to test noise rejection
  - Sinusoidal background with frequency = 2x current, amplitude = 10x to 1,000x fluorescence
  - Gaussian background noise, amplitude =2x fluorescence
- Both methods achieve similar (very good) noise rejection with purely sinusoidal background noise
- Boxcar averager method required averaging ~50 simulated laser scans to achieve similar results to single laser scan with sample-hold method with 2x Gaussian noise
  - Approx. 750,000 current cycles averaged for each wavelength at 3 kHz



Pressure vs. Broadening in Xe Lamp

- From Cedolin thesis
  - Voigt parameter, a = 2.7 in our lamp corresponds to ≈ 7 torr

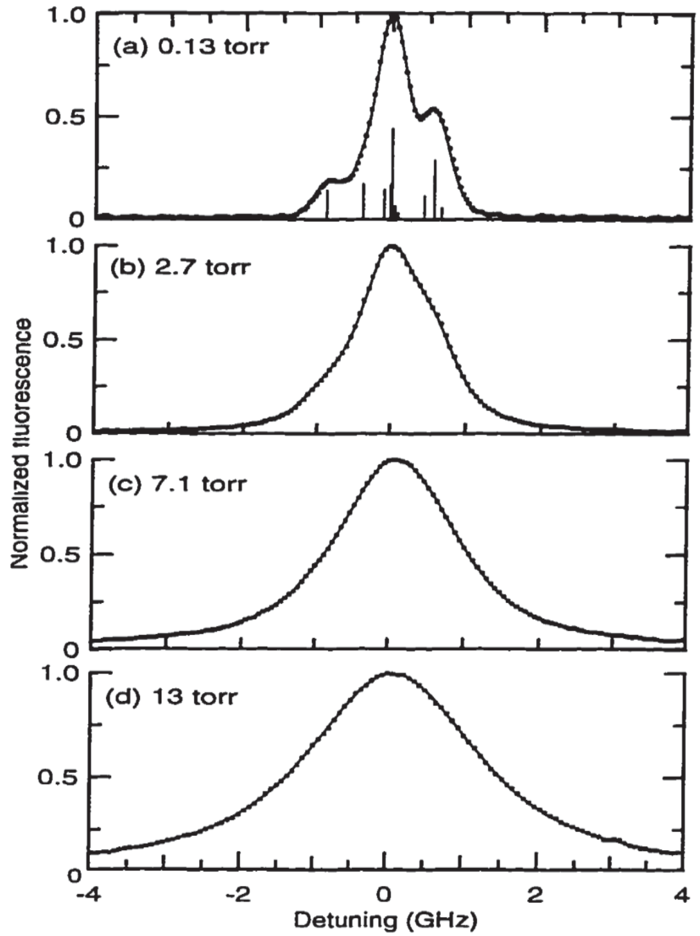


FIG. 4-4. Evolution of reduced 828-nm LIF excitation line shapes (•) and curve-fit results (—) with density: (a) 3.9×10^{21} atoms m^{-3} with contributing hyperfine lines (|), only every sixth point plotted for clarity, Voigt $a = 0.16$; (b) 8.4×10^{22} atoms m^{-3}, every tenth point plotted, $a = 1.2$; (c) 2.2×10^{23} atoms m^{-3}, every tenth point plotted, $a = 2.8$; (d) 4.0×10^{23} atoms m^{-3}, every twenty-fifth point plotted, $a = 4.9$.